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MAGNETOGRAVITATIONAL INSTABILITY OF ANISOTROPIC PLASMA WITH HALL EFFECT*

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1. INTRODUCTION

The problem of the magnetogravitational instability of interstellar matter is of considerable importance in connection with protostar and star formation in magnetic dust clouds. The initial analysis of gravitational instability in an infinite homogenous medium is due to Jeans (1929) who derived the expression for the maximum size of a uniform gravitating mass which is stable to small fluctuations in density. This analysis has been extended in recent years to include a variety of other effects, e.g., isotropic turbulence (Chandrasekhar, 1951), rotation (Chandrasekhar, 1954; Bel and Schatzman, 1958) and uniform magnetic field (Chandrasekhar and Fermi, 1953). It has been shown that a uniform magnetic field and rotation (or even both together) leave the Jeans' criterion for fragmentation unchanged. Furthermore, it is also found that the transport processes like finite electrical conductivity and viscosity do not modify Jeans' formula (Pacholczyk and Stadolkiewicz, 1960).

In all investigations on magnetogravitational stability reported so far (Pacholczyk, 1963), the scalar pressure approximation has been used. The interstellar medium, is, however, very dilute and the interparticle collisions are too infrequent so that in the presence of the interstellar magnetic field, the plasma pressure is likely to assume a tensorial character, with unequal magnitudes parallel and perpendicular to the magnetic field. If this anisotropy becomes large enough, it may lead to instability in an otherwise stable system. Further Ware (1961) pointed out that an important factor which has hitherto been ignored in various stability investigations is the Hall effect. He suggested, without, however, solving any definite problem that when the Hall effect is included, a growing wave instability (overstability) should replace the pure instability as predicted by the ideal magnetohydrodynamic equations. It is felt that the Hall effect assumed importance in a low density plasma such as interstellar space.

With this viewpoint, we investigate, in the present note, the problem of the magnetogravitational instability of a static, unbounded, inviscid, homogenous, gravitating plasma including finite conductivity and Hall effect. We assume the plasma to be carrying a uniform magnetic field so that the physical conditions prevalent in the medium require the gas pressure to be anisotropic. We shall be making use of the "Double-Adiabatic" hydromagnetic equations (Chew, Goldberger and Low, 1956).

2. PERTURBATION EQUATIONS AND DISPERSION RELATION

Neglecting heat flow tensor, we may write the linearized equations for the problem under considerations as,

$$\zeta_0 \frac{\partial v}{\partial t} = -\nabla \cdot \delta p + \rho_o \nabla \delta U + \frac{L}{4\pi}(\nabla \times h) \times H. \tag{1}$$

$$\frac{\partial}{\partial t} \delta \rho = -\rho_o \nabla \cdot v \tag{2}$$

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$$\nabla^2\delta U = -4\pi G\delta\rho \tag{3}$$

$$\frac{\partial L}{\partial t}=\nabla\times(v\times H_o)+\eta\nabla^2 h-\frac{c}{4\pi ne}\nabla\times[(\nabla\times h)\times H_o]+\frac{c^2}{4\pi\omega\rho^2}\frac{\partial}{\partial t}\nabla^2 h \tag{4}$$

$$\nabla\cdot h=o \tag{5}$$

$$\frac{\delta p_\parallel}{p_\parallel}=3\frac{\delta\rho}{\rho_o}-2\frac{h_z}{H_o} \tag{6}$$

$$\frac{\delta p_\parallel}{p_\parallel}=\frac{\delta\rho}{\rho_o}+\frac{h_z}{H_o} \tag{7}$$

Here $\eta=c^2/4\pi\sigma$ (σ being the electrical conductivity) and $\omega\rho=\sqrt{\frac{4\pi ne^2}{m}}$ (plasma frequency). Further V, $\delta\rho$, δU, h, $\delta p_\parallel$, $\delta p_\perp$ denote respectively the velocity vector, perturbations in density, gravitational potential, magnetic field vector, plasma pressure parallel and perpendicular to the initial magnetic field H_0. $p_\parallel$ and $p_\perp$ represent the constant components of pressure (along and perpendicular to the magnetic field respectively) of the pressure tensor $\underset{\leftrightarrow}{p}$ given by,

$$\underset{\leftrightarrow}{p}=p_\parallel n\cdot n+p_\perp(l-n\cdot n) \tag{8}$$

where n is a nuit vector along the magnetic field and l is lunit dyadic.

Choosing the orientation of the coordinate axes such that $H_0=(0,0H_0)$ and seeking solutions which are independent of y and whose dependence on x, z, and t is of the form exp. $(ik_x x+ik_z z+\omega t)$, we rewrite the equations (1) to (5) as,

$$\rho_0\omega\nu_x=-ik_x\delta p_\perp-ik_z(p_\parallel-p_\perp)\frac{h_x}{H_0}+ik_x\rho_0\delta U+\frac{H_0}{4\pi}(ik_z h_x-ik_x h_z) \tag{9}$$

$$\rho_0 u\nu_y=-ik_z(p_\wedge-p_\perp)\frac{hy}{H_0}+ik_z\frac{H_0}{4\pi}h_y \tag{10}$$

$$\rho_0\omega\nu_z=-ik_z\delta p_\parallel+ik_z(p_\parallel-p_\perp)\frac{h_z}{H_0}+ik_z\rho_0\delta U \tag{11}$$

$$\omega\delta\rho=-\rho_0\nabla\cdot v \tag{12}$$

$$\delta U=-\frac{4\pi G\rho_0}{k^2}\nabla\cdot v \tag{13}$$

$$\left\{\omega\left(1+\frac{c^2}{4\pi\omega\rho^2}k^2\right)+\eta k^2\right\}h_x=ik_z H_0\nu_x-\frac{c}{4\pi ne}k_z^2 H_0 hy \tag{14}$$

$$\left\{\omega\left(1+\frac{c^2k^2}{4\pi\omega\rho^2}\right)+\eta k^2\right\}h_y=ik_z H_0\nu_y-\frac{c}{4\pi ne}ik_z H_0(ik_z h_x-ik_x h_z) \tag{15}$$

$$\left\{\omega\left(1+\frac{c^2k^2}{4\pi\omega\rho^2}\right)+\eta k^2\right\}h_z=-H_0(\nabla\cdot v-ik_z\nu_z)-\frac{c}{4\pi ne}H_0 ik_x k_z h_y \tag{16}$$

$$ik_x h_x-ik_z h_z=o \tag{17}$$

Taking divergence of equation (1), and using equation (3), we get

$$\rho_0\omega\nabla\cdot v=-\nabla\cdot(\nabla\cdot\delta\underset{\leftrightarrow}{p})-4\pi G\rho_0\delta\rho+\frac{H_0}{4\pi}k^2h_z \tag{18}$$

where

$$k^2 = k_x{}^2 + k_z{}^2.$$

The first term on the right hand side of equation (18) is written with the help of equations (6) and (7) as,

$$-\nabla\cdot(\nabla\cdot\delta p) = -\frac{h_z}{H_0}\left[2k_z^2(2p_\parallel - p_\perp) - k_x^2 p_\perp\right] - \frac{\nabla\cdot v}{\omega}\left[k_x^2 p_\perp + 3k_z^2 p_\parallel\right] \tag{19}$$

Through a process of elimination wherein we use the equations (9), (11), (14), (15) and (17) we obtain,

$$h_z\left[A + \left(\frac{c}{4\pi ne}\right)^2 \frac{H_0^2 k_1^2 k_z^2}{A + \frac{k_z^2}{\rho_0\omega}\left(\frac{H_0^2}{4\pi} - p_\parallel + p_\perp\right)}\right] = -H_0(\nabla\cdot v - ik_z v_z) \tag{20}$$

where

$$A = \omega\left(1 + \frac{c^2k^2}{4\pi\omega\rho^2}\right) + \eta k^2 \tag{21}$$

Substituting equations (12), (19) and (20) in equation (18), we get

$$\frac{\nabla\cdot v}{\omega}\left[\rho_0\omega^2 + \frac{\omega\left\{\frac{k^2H_0^2}{4\pi} - 2k_z^2(2p_\parallel - p_\perp) + k_x^2 p_\perp\right\}}{A + \left(\frac{c}{4\pi ne}\right)^2 \frac{H_0^2 k^2 k_z^2}{A + \frac{p_z^2}{\rho_0\omega}\left(\frac{H_0^2}{4\pi} - p_\parallel + p_\perp\right)}} + (3p_\parallel k_z^2 + k_x^2 p_\perp - 4\pi G\rho_0^2)\right]$$

$$= ik_z v_z\left\{\frac{k^2H_0^2}{4\pi} - 2k_z^2(2p_\parallel - p_T) + k_x^2 p_\perp\right\}\left\{A + \left(\frac{c}{4\pi ne}\right)^2 \frac{H_0^2 k^2 k_z^2}{A + \frac{k_z^2}{\rho_0\omega}\left(\frac{H_0^2}{4\pi} - p_\parallel + p_\perp\right)}\right\}^{-1} \tag{22}$$

The expression for $\nabla\cdot v$ in terms of v_z is now obtained from equation (11), using equations (6), (7) and (20). We get

$$\nabla\cdot v = v_z \frac{\left[\rho_0\omega + \frac{k_z^2(3p_\parallel - p_\perp)}{A + \left(\frac{c}{4\pi ne}\right)^2 \frac{H_0^2k^2k_z^2}{A + (H_0^2/4\pi - p_\parallel + p_T)k_z^2/\rho_0\omega}}\right]}{ik_z\left[\frac{3p_\parallel - 4\pi G\rho_0^2/k^2}{\omega} - \frac{(3p_\parallel - p_\perp)}{A + \left(\frac{c}{4\pi ne}\right)^2 \frac{H_0^2k^2k_z^2}{A + \frac{k_z^2}{\rho_0\omega}\left(\frac{H_0^2}{4\pi} - p_\parallel + p_\perp\right)}}\right]} \tag{23}$$

From equations (22) and (23) we finally obtain the dispersion relation as,

$$[\rho_0\omega^2 + 3p_\parallel k_z^2 + k_x^2 p_\perp - 4\pi G\rho_0^2]\left[\omega\rho_0\left\{A + \left(\frac{c}{4\pi ne}\right)^2 \frac{H_0^2k^2k_z^2}{A + \frac{k_z^2}{\rho_0\omega}\left(\frac{H_0^2}{4\pi} - p_\parallel + p_\perp\right)}\right\} + k_z^2(3p_\parallel - p_\perp)\right]$$

$$+\left[\frac{k^2H_0^2}{4\pi} - 2k_z(2p_\parallel - p_\perp) + k_x^2 p_\perp\right]\left[\omega\,\rho_0\quad k_z^2\left(3p_\parallel - \frac{4\pi G\rho_0^2}{k^2}\right)\right] = 0 \tag{24}$$

The equation (24) reduces without the Hall effect to the one obtained in an earlier paper (Tandon and Talwar, 1963) with $\Omega=0$.

3. DISCUSSION OF THE DISPERSION RELATION

The dispersion relation (24) is a sixth order equation in ω, the parameter to decide the question of the stability of the configuration. We shall, however, simplify our discussion by considering the following special cases.

Case (i) Transverse Propagation

In the case of transverse propagation ($k_x=k$, $k_z=0$), the dispersion relation assumes the simple form,

$$\omega^2+\frac{\omega}{A}[V^2+S_\perp^2]k^2+(k^2S_\perp-4\pi G\rho_0)=0 \tag{25}$$

where $V^2=H_0^2/4\pi P_0$, $S_\perp^2=p_\perp/P_0$ and the parameter A is given by equation (21).

The equation (25) is rewritten as,

$$\omega^3\left(1+\frac{c^2k^2}{4\pi\omega_p^2}\right)+\eta\omega^2k^2+k^2\omega\left[V^2+S_\perp^2+\left(1+\frac{c^2k^2}{4\pi\omega_p^2}\right)\left(S_\perp^2-\frac{4\pi G\rho_0}{R^2}\right)\right]+\eta k^2(k^2S_\perp^2-4\pi G\rho_0)=0 \tag{26}$$

For plasma with infinite electrical conductivity ($\eta=0$) and $\omega_p\to\infty$, we conclude that the configuration is unstable for transverse propagation vector less than a certain critical value k^* given by

$$k_*^2=\frac{4\pi G\rho_0}{V^2+2S_\perp^2} \tag{27}$$

On the other hand if the conductivity were finite the equation (27) gives,

$$k_*=\sqrt{\frac{4\pi G\rho_0}{S_\perp^2}} \tag{28}$$

as the critical wave number below which any perturbation increases its amplitude monotonically till the linear theory breaks down. Further the equation (26) admits two complex conjugate roots with positive real part. It therefore follows that irrespective of the fact that the system is self-gravitating or not, there are present, for transverse propagation in a finitely conducting medium alone, growing wave instability (overstability).

Case (ii) Parallel Propagation

With $k_z=k$, $k_x=0$ and restricting ourselves to infinitely conducting configuration but retaining the Hall current term, we obtain the dispersion relation as,

$$[\omega^2+3k^2S_\parallel^2-4\pi G\rho_0]\left[\{\omega^2+k^2(V^2+S_\perp^2-S_\parallel^2)\}^2+\left(\frac{c}{4\pi ne}\right)^2H_0^2k^4\omega^2\right]=0 \tag{29}$$

This gives a gravitational mode uncoupled with the other two modes which involve the Hall effect term. The gravitational mode leads to instability provided $k<k^*$ where k^* is given by,

$$k^*=\sqrt{\frac{4\pi G\rho_0}{3S_\parallel^2}} \tag{30}$$

For a non-gravitating plasma, the instability could result from the second factor in equation (29). The non-gravitating configuration shall be stable if $(S_\parallel^2-S_\perp^2-V^2)\leqslant 0$. On the other hand if

$(S_{\parallel}^2-S_{\perp}^2-V^2)>0$, the configuration without Hall term is unstable for all modes of disturbance (Lüst, 1960). In our present context there is no instability for wave numbers greater than a certain critical value k_c given by,

$$k_c^2=\frac{2(S_{\parallel}^2-S_{\perp}^2-V^2)}{(c/4\pi ne)^2H_0^2} \tag{31}$$

We, therefore, conclude that the mode of disturbance (in range k_c to ∞) which leads to instability in a configuration devoid of Hall effect, is stabilized by the Hall effect, athough the Hall effect is unable to suppress instability for all wavelengths.

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THE DETECTION OF SOLAR NEUTRINOS*

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An old dream of nuclear physicists has now entered the realm of possibility. Raymond Davis of Brookhaven National Laboratory has the plans for an apparatus capable of detecting the flux of neutrinos from the sun. The Brookhaven Solar Neutrino Observatory, as this equipment is called, will be built in future years and buried thousands of feet underground. Then, for the first time a direct "view" into the center of the sun will be possible.

Neutrino astronomy is quite new, but physicists have in recent years become increasingly involved with these elementary particles. The story of neutrinos goes back to the early days of nuclear physics (about 1935), when a number of disturbing facts came to light.

For instance, the beta disintegration (emission of a negative electron) of certain nuclei showed no sign of conserving energy and momentum. An important case (discovered later) was the observed decay of a neutron into a proton and an electron. Analysis of this process showed that the sum of the energies of the proton and electron (including the rest mass) was *smaller* than the total energy of the neutron. Further, this sum was not constant but varied according to the particular neutron observed. It was also discovered that the two emerging particles did not move in opposite directions (as would be expected from a neutron at rest), but were directed in many possible ways, as in Fig. 1.

To overcome these difficulties, W. Pauli postulated the existence of a third, unobserved particle emitted during beta decay. This particle—neutral and massless, like a photon of light—carried off the balance of the energy and momentum; it was later named *neutrino*. According to the principles of quantum mechanics, it could be detected by a reaction inverse to the one responsible for its birth. For example, a neutron could absorb a neutrino and give rise to a proton and an electron. But calculations showed that the probability of capture was extremely small, far below the detection power of existing equipment. This explains why the presence of neutrinos had not been felt before in physics.

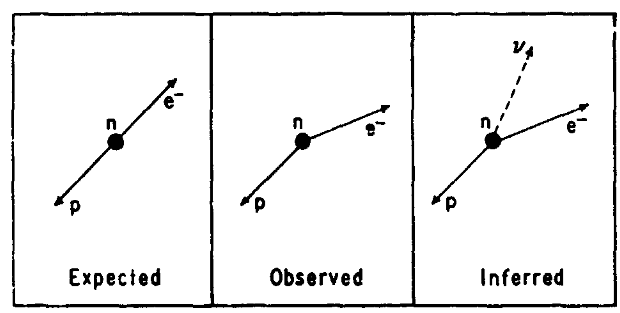

FIGURE 1.—The dynamics of neutron decay, in which the lack of symmetry gave rise to the prediction that an unknown particle was present. In the third section this particle, a neutrino, is symbolized by the Greek letter nu (ν).

Later it was shown that this particle existed in two brands: neutrinos and antineutrinos. The only difference between them that is important to us concerns their origins. Neutrino births accompany the beta decay of protons (in complex nuclei for energy considerations), and antineutrinos are born when neutrons undergo beta decay. Inversely, a neutrino can be captured only by a neutron, an antineutrino only by a proton.

As physicists developed beta-decay theory, close agreement between its predictions and the experiments gave abundant indirect evidence for the existence of neutrinos. It soon became clear that they had reality and were not mere artifices of thought; they became accepted in physics on the same footing as other elementary particles.

Experimental detection of neutrinos had to wait many years. But World War II gave tremendous

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impetus to nuclear physics technology, and created huge antineutrino sources in the form of nuclear reactors. Their production of neutron-rich isotopes roused hopes that finally materialized in 1958, when F. Reines and C. L. Cowan, Jr., succeeded in detecting antineutrinos coming from the Savannah River reactor. Although their detection apparatus was exposed to a flux of about 10^{13} antineutrinos per square centimeter per second, the counted number was, at best, a few per hour. The antineutrino capture probability was thus very small indeed, but it agreed with the prediction made in the early days of neutrino theory. Elusive as the neutrino is, belief in its existence has an excellent foundation both in experiment and theory.

Recently it has been shown that two other types of neutrinos exist, related to the decay of muon particles.

NEUTRINOS AND ASTRONOMY

Nuclear physics has brought an answer to a very old problem: Where does the sun find the energy that it has been radiating for so many eons? Around 1938, Hans Bethe showed convincingly that the centers of the sun and other stars are seats of intense thermonuclear reactions. Both the liberation of energy and the formation of new isotopes occur in these stellar nuclear furnaces. Analysis of the network of reactions taking place showed that interspersed among some purely nuclear reactions were a certain number of beta-decay processes—hence, neutrino-emitting reactions.

But even a star is not thick enough to absorb traveling neutrinos appreciably. Proper shielding would require a few billion stars lined up one after another! The sun is essentially transparent to neutrinos, which escape, carrying away their energy. Any proper study of stellar interiors has to take this escape into account: the solar furnace must be hotter to make up for the loss.

In the sun this effect is only a few percent. But its immediate consequence is that an appreciable neutrino flux reaches the earth, about 6.5×10^{10} neutrinos per square centimeter per second. The flux of antineutrinos from the sun is negligibly small, since most solar nuclear reactions are of the proton-capture type, forming proton-rich neutrino-emitting isotopes.

SOLAR NEUTRINOS

Basically, the source of the sun's energy is the conversion of four hydrogen atoms into one helium atom. Under stellar conditions, the transformation is accomplished through four main channels, the so-called PP branches illustrated in Fig. 2. Notice that each of these branches includes neutrino emission.

In each process, the numbers of neutrinos having different energies follow a specific pattern. As illustrated in Fig. 3 for neutrinos from hydrogen, most emitted particles belong to a broad hump, but there is also a sizable peak of particles all with about the same energy—some one million electron volts greater than the maximum energy in the hump. For certain nuclei, such as beryllium-7, *two* peaks of monoenergetic neutrinos are emitted, since the beta decay sometimes goes to an excited state of lithium-7.

The PP Chain

$$\begin{array}{rcll}
H^1 + H^1 & \rightarrow & D^2 + \beta^+ + \nu & \\
D^2 + H^1 & \rightarrow & He^3 + \gamma & \text{PP I} \\
He^3 + He^3 & \rightarrow & He^4 + 2\,H^1 & \\
 & \text{or} & & \\
He^3 + He^4 & \rightarrow & Be^7 + \gamma & \\
Be^7 + e^- & \rightarrow & Li^7 + \nu + \gamma & \text{PP II} \\
Li^7 + H^1 & \rightarrow & 2\,He^4 & \\
 & \text{or} & & \\
Be^7 + H^1 & \rightarrow & B^8 + \gamma & \\
B^8 & \rightarrow & Be^8 + \beta^+ + \nu & \text{PP III} \\
Be^8 & \rightarrow & 2\,He^4 &
\end{array}$$

The CNO Cycle

$$\begin{array}{rcll}
C^{12} + H^1 & \rightarrow & N^{13} + \gamma & \\
N^{13} & \rightarrow & C^{13} + \beta^+ + \nu & \\
C^{13} + H^1 & \rightarrow & N^{14} + \nu & \text{PP IV} \\
N^{14} + H^1 & \rightarrow & O^{15} + \gamma & \\
O^{15} & \rightarrow & N^{15} + \beta^+ + \nu & \\
N^{15} + H^1 & \rightarrow & C^{12} + He^4 &
\end{array}$$

FIGURE 2.—Nuclear reactions responsible for energy generation in the sun. In some of the proton-proton series, later reactions depend on earlier ones. Greek letter symbols are $\beta+$ (positron), γ (gamma ray), and ν (neutrino).

Before we can evaluate the neutrino energy spectrum from the sun, and compute the mean energy, we must specify the conditions in the solar interior. Indeed, a first step is to find the contribution of each PP branch to the sun's total energy output.

Using the most recent data about nuclear energy generation rates and stellar opacities, we have computed a solar model whose evolution during the past 4½ billion years is described in Table I. For completeness, we include the changing luminosity, adius, surface and central temperatures, and ther

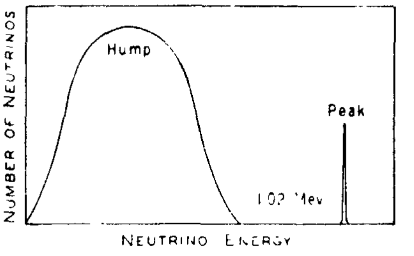

FIGURE 3.—The energy spectrum of neutrinos coming from hydrogen nuclei. The hump is the result of processes involving creation of an electron during the decay, while the peak indicates processes involving the capture of an orbital or a free electron by the decaying nucleus.

TABLE I.—*Evolution of the Sun*

Billions of years ago	4.5	3.6	2.7	1.8	0.9	Now
Luminosity	0.73	0.77	0.83	0.87	0.92	1.00
Radius	0.95	0.95	0.97	0.98	0.99	1.00
Surface temperature (degrees Kelvin)	5,400	5,500	5,500	5,600	5,600	5,800
Central temperature (millions of degrees)	14	15	15	15	16	16
Central density	89	98	110	120	140	170
Percent hydrogen	68	61	53	46	38	31
% PP I	86	82	79	71	64	56
% PP II	13	17	22	28	34	40
% PP III	0.004	0.008	0.01	0.02	0.03	0.05
% PP IV	0.4	0.06	0.9	1.3	2.0	3.2

Luminosity and radius are in terms of the present value for the sun, central density in grams per cubic centimeter. The percentage of hydrogen is in terms of the sun's mass. The last four lines give the percentage of the total energy provided by the four different reactions.

central density and central hydrogen abundance. But note particularly the last four lines of the table, which give the fractional contribution of each PP branch. We see that more than half the sun's energy has come from PP I during the past 4½ billion years. The PP II branch has been slowly increasing in importance until it now provides 40 percent of the sun's energy. On the other hand, the remaining two branches appear to be relatively unimportant.

Our computations have included a detailed calculation of how temperature, pressure, and other properties change from the center out to the surface of the present sun. This permitted a further computation that gave the relative contributions of the four PP branches at different levels in the solar interior. Finally, we could predict the neutrino energy spectrum of the sun, illustrated in Fig. 4.

From this chart we see the relative importance of different neutrino sources over the whole energy range. For instance, the hump marked H represents the reaction where two protons unite to form a deuteron, positron, and neutrino (see the first line of PPI in Fig. 2). At an energy of 0.3 million electron volts, it rises to a flux of about three neutrinos per square centimeter each second per million electron volts. Almost the same flux comes from the peak H′, for the combination of two protons and an electron to yield a deuteron and neutrino (not included in Fig. 2).

The most prominent features are the two peaks of beryllium-7, which rise to 47 and 344 but are very narrow. Although the neutrinos from boron-8 are very rare, they turn out to be the most important, because their high energies mean very large capture cross sections and hence easier detection. Since this chart has been normalized to

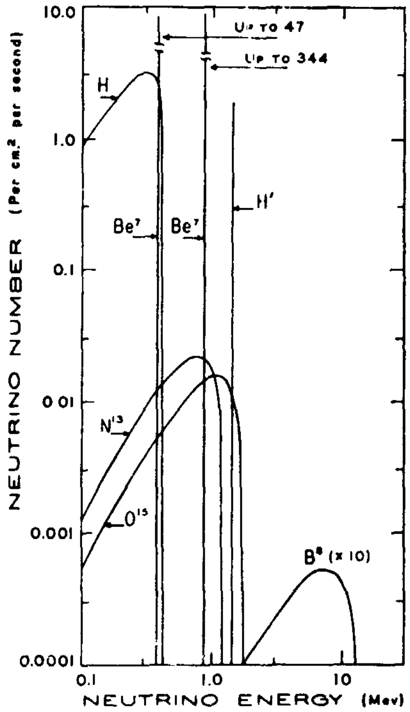

FIGURE 4.—The neutrino energy spectrum of the sun, normalized to one particle in the entire flux. The horizontal scale is in millions of electron volts. Capture of free electrons by beryllium-7 nuclei and by protons (H') results in very narrow, high peaks. Their heights depend on density and temperature in the sun's interior.

one neutrino over the whole energy range, to obtain the flux at the earth multiply ordinate values by 6.5×10^{10}.

DETECTING SOLAR NEUTRINOS

A neutrino, as we have seen, can be captured by a neutron (either free or in a complex nucleus). Since free neutrons are not readily available, a detection system must utilize some suitable isotope. A very good choice is chlorine-37, which can react with a neutrino to yield argon-37 and an electron.

For capture by chlorine-37 to take place, an incident neutrino must have an energy of at least 0.814 million electron volts. And above this limit, high-energy neutrinos have a much better chance of inducing the reaction, since the collision cross section is proportional to the square of the energy of the out-coming electron.

Looking back at Fig. 4 with these facts in mind, we see at once that most of the solar neutrinos are not capable of inducing this reaction. Indeed, we lose all the neutrinos from the hump of the proton-proton reaction, and all the neutrinos from the first beryllium-7 peak.

In fact, a recent calculation by J. N. Bahcall shows that of every 100 solar neutrinos captured by a chlorine-37 detector, about eight will come from the higher beryllium-7 peak and about 92 from the boron hump. Negligible contributions come from the other neutrino-producing processes. The total probability of a capture per target nucleus of chlorine-37 will be as low as 4×10^{-35} per second.

This means that any feasible detection apparatus must be enormous! Indeed, multiplying this rate by the number of chlorine atoms will give the probability of an event per second in the detector. Since practical considerations require a counting rate not much smaller than one a day, the detector must contain about 10^{30} chlorine atoms. At the present time, Dr. Davis considers the experiment perfectly feasible.

THE DETECTING EQUIPMENT AND ITS OPERATION

In his first attempt, Dr. Davis has worked with a 1,000-gallon and later a 3,000-gallon tank of carbon tetrachloride (CCl_4). Now he uses perchlorethylene (C_2Cl_4) as it is less toxic and has a lower vapor pressure. The estimate noted in this article has required him to consider a detecting tank holding 100,000 gallons of material (2.2×10^{30} atoms of chlorine-37). This amount of liquid would fill 40 tank trucks of the usual size one sees on the highway!

Before use, the filled tank has to be cleansed of all argon atoms already there from atmospheric contamination or other sources. The procedure is to sweep helium bubbles through the liquid. Then the tank is left to rest, exposed as always to the effect of solar neutrinos. Gradually, at a rate of about one per day, chlorine-37 atoms are transformed into argon-37 by the reactions. However, the argon-37 is naturally radioactive, and through beta decay changes back to chlorine-37 in about 35 days, so it does not pay to wait too long. In fact, after a few months, the concentration of argon-37 saturates and remains at the same level indefinitely.

Therefore, after about 100 days the tank will again be swept clear of argon. Then the helium will be removed from the argon by another chemical process, and the argon atoms will be gathered in small containers. Among various other isotopes, the argon contains argon-37 produced by neutrino reactions. Through their beta disintegration, these atoms will produce a signal measurable by standard nuclear physics techniques, thus making their presence known.

As can well be imagined, the major problem is background. A large number of other processes may give exactly the same final result, and the experimentalist must make absolutely sure that the counts he registers in his counter are really from argon-37 generated by solar neutrinos. The tank is close to the impossible, and requires the utmost skill of the experimental nuclear chemist. For instance, to avoid competition by cosmic rays in producing this reaction, the tank and all the chemical equipment will have to be buried far beneath the surface of the earth. Present indications are that the tank is to be located in a mine at a depth of several thousand feet, in a room specially excavated to hold all the apparatus. So far, the whole experiment is on paper, except for the detection apparatus, which is partly set up at Brookhaven, New York. We hope that construction will start soon, and that there will be some results within a few years.

WHAT CAN WE LEARN FROM SOLAR NEUTRINOS?

If the experiment is successfully carried through, one possibility is that we will find just what has been predicted. This in itself would be a major feat. All that we know directly about the sun has come from observations of its surface layers. We have been able to explore the interior only by applying point by point the differential equations of theoretical physics. Thus, we have only highly indirect evidence of conditions deep inside the

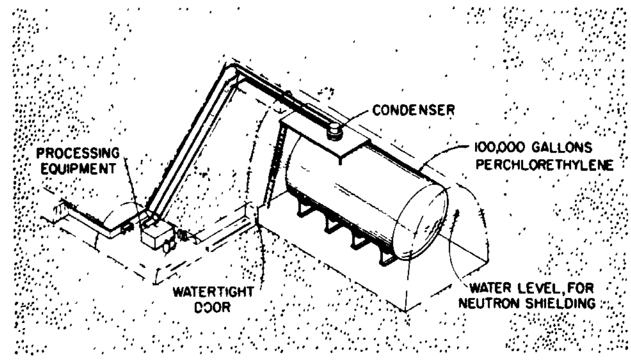

FIGURE 5.—A plan for the Brookhaven observatory that may detect neutrino emission from the sun. In this enormous tank, roughly 20 feet in diameter and 40 feet long, the nuclear chemist will have to fish for perhaps 100 atoms of radioactive argon–37 generated by chlorine-neutrino interactions. Illustration courtesy Raymond Davis.

sun, from which the nuclear reactions taking place there must be analyzed. The weight of indirect evidence should not be underestimated, but it would be very desirable to obtain *direct* information on the center of the sun, and to verify that our understanding of the processes there is correct. In particular, the rate of neutrino emission would provide a sensitive test of the adopted central temperature. There is also a rather remote possibility that some important physical factors, as yet unknown, are operating inside the sun. The history of science teaches us about many such upsets.

Is it possible that the neutrino flux from the sun varies with time, for instance with the solar cycle? Most solar experts consulted believe this unlikely. But we really cannot tell beforehand what will come from this and some other suggested problems for the solar neutrino observatory. In any event, it is a new channel of information for solar physics, and should be thoroughly explored. We are all waiting for the first clicks in Dr. Davis' immense tank.